Doubly heavy baryons production within NRQCD at CEPC

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In collaboration with J.-J. Niu, J.-B. Li, and H.-Y. Bi, based on arXiv:2305. 15362

CEPC味物理-新物理和相关探测技术研讨会

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Content

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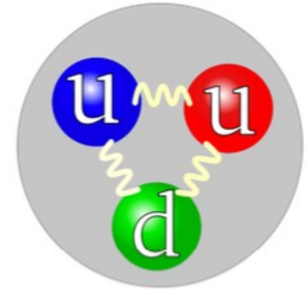
Content

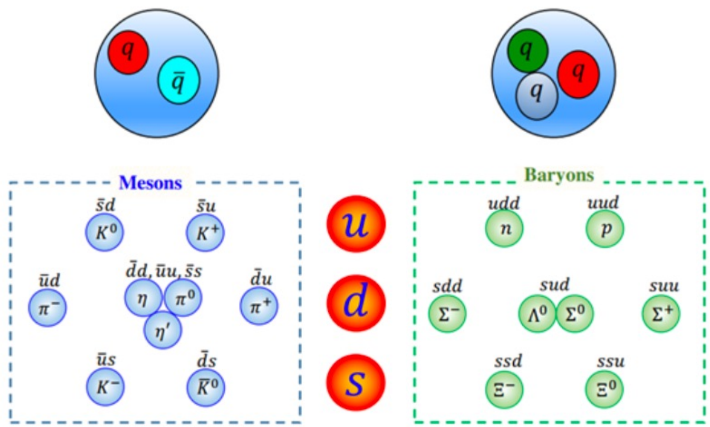
Background

Quark model

- QCD quark confinement
- Quark has fractional charges



In 1964, Gell-Mann and Zweig proposed a way, quark model, to build the numerous hadrons out of three fundamental quarks.

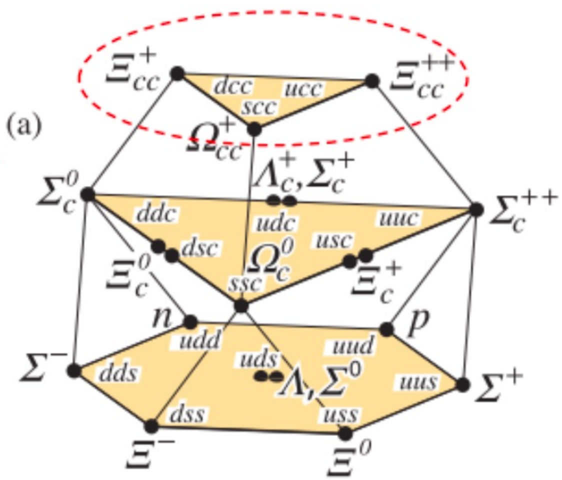


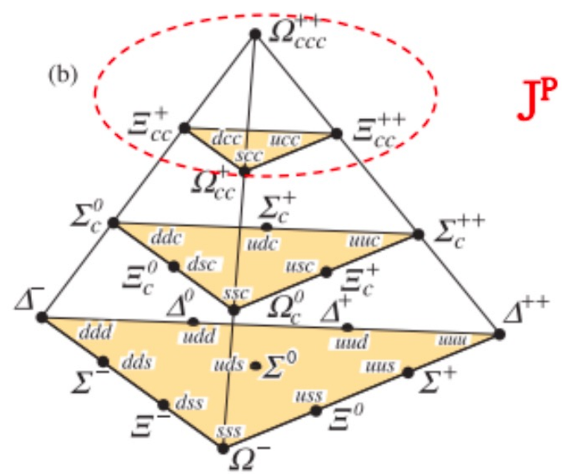
M. Gell-Mann, Phys. Lett. 8, 214 (1964).

Background

Quark model extending to SU(4), a 20-plet for $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, respectively.

$J^P = 1/2^+$





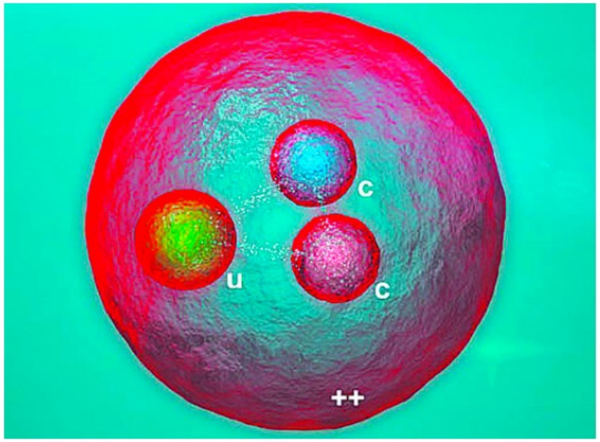
$J^P = 3/2^+$

Searching for doubly/triply heavy baryons would be important for the spectroscopy and QCD studies

Background

Observation of doubly charmed baryon

科技部发布2017年度中国科学十大进展



$\Lambda_c^+ K^- \pi^+ \pi^+$ Published in *Phys. Rev. Lett. 119, 112001 (2017).*

GENXICC *C. H. Chang, X. G. Wu et al, Comput. Phys. Commun, (2007, 2010).*

Background

Observation of heavy hadrons

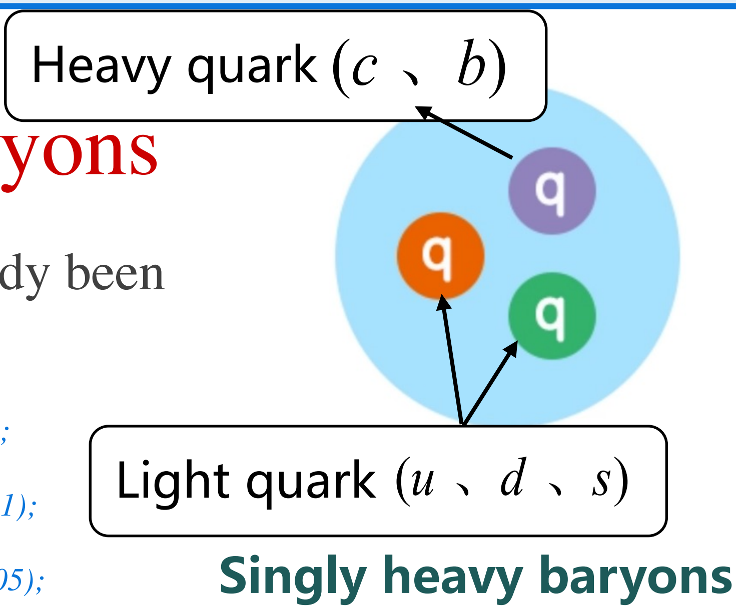
- B_c meson is the only doubly flavoured meson.
- Ξ_{cc}^{++} baryon is the only observed doubly flavoured baryon.
- The results are available only at the hadron collider.

J/Ψ, 德国汉堡, 1974 (1976 诺奖)
$\downarrow$
Υ, Fermilab, 1977
$\downarrow$
B_c, CDF, 1998.
$\downarrow$
Ξ_{cc}^{++}, LHCb, 2017.

Heavy baryons : singly-, doubly- and triply-heavy baryons

Background

Observation of singly heavy baryons



All ground-state singly heavy baryons had already been observed except Ω_b^* with $J^P = 3/2^+$

S.-H. Lee et al. (Belle Collaboration), Phys. Rev. D 89, 091102 (2014);

T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D 84, 012003 (2011);

B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 72, 052006 (2005);

R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 122, 012001 (2019);

R. L. Workman et al. (Particle Data Group), PTEP 2022, 083C01 (2022).

Some excited P-wave singly heavy baryons had also been announced.

E. Santopinto, A. Giachino, and et al, The Eur. Phys. J. C 79, 1012 (2019)

R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 124, 082002 (2020).

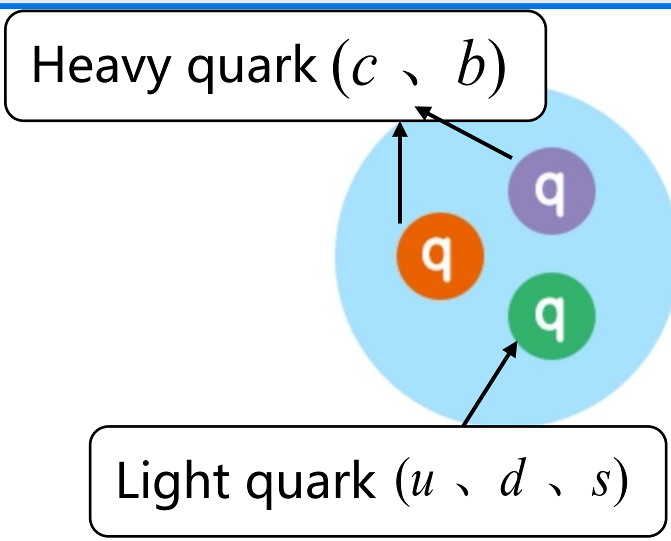
R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 124, 222001 (2020).

T. J. Moon et al. (Belle Collaboration), Phys. Rev. D 103, L111101 (2021).

R. Aaij et al. (LHCb Collaboration), JHEP 2016, 161 (2016).

Background

Motivations



Doubly heavy baryons

- Search for Ξ_{bc} and Ξ_{bb} ;
- Precise test of Standard model or quark model;
- Sack of the theoretical study on excited heavy doubly baryons;

NRQCD is an effective nonrelativistic theory that describes the interactions of quarks and antiquarks in hadronic systems

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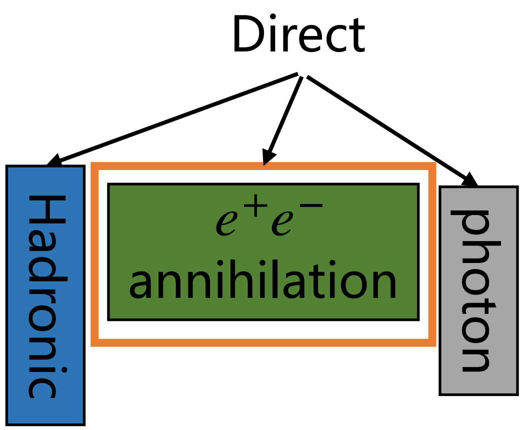
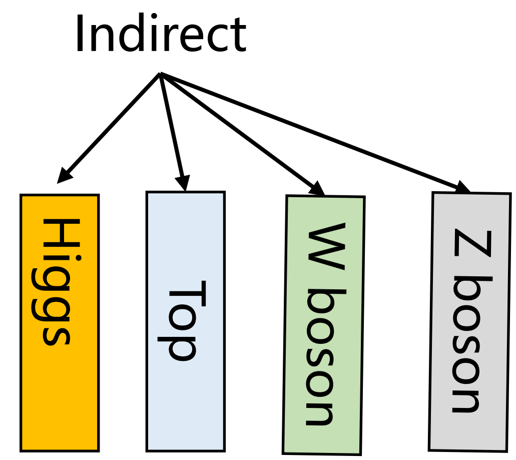
A. F. Falk, M. E. Luke, M. J. Savage and M. B. Wise, Phys. Rev. D 49, 555-558 (1994).

Background

Direct and indirect production mechanisms for the production of doubly heavy baryons





C. H. Chang, C. F. Qiao, J. X. Wang and X. G. Wu, Phys. Rev. D 73, 094022 (2006).
C. H. Chang, J. P. Ma, C. F. Qiao and X. G. Wu, J. Phys. G 34, 845 (2007).
J. P. Ma and Z. G. Si, Phys. Lett. B 568, 135 (2003).
S. P. Baranov, Phys. Rev. D 54, 3228 (1996).

X. C. Zheng, C. H. Chang and Z. Pan, Phys. Rev. D 93, 034019 (2016).
J. Jiang, X. G. Wu, Q. L. Liao, X. C. Zheng and Z. Y. Fang, Phys. Rev. D 86, 054021 (2012).
J. Jiang, X. G. Wu, S. M. Wang, J. W. Zhang and Z. Y. Fang, Phys. Rev. D 87, 054027 (2013).

G. Chen, X. G. Wu, Z. Sun, Y. Ma and H. B. Fu, JHEP 1412, 018 (2014).
H. Y. Bi, R. Y. Zhang, X. G. Wu, W. G. Ma, X. Z. Li and S. Owusu, Phys. Rev. D 95, 074020 (2017).
S. Y. Li, Z. G. Si and Z. J. Yang, Phys. Lett. B 648, 284 (2007).

*J. J. Niu, L. Guo, **H. H. Ma** and X. G. Wu, Eur. Phys. J. C 79, no.4, 339 (2019).*
***H. H. Ma** and J. J. Niu, Eur. Phys. J. C 83, no.1, 5 (2023)*

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***H. H. Ma**, J. J. Niu and X. C. Zheng, Phys. Rev. D 107, no.1, 014006 (2023)*

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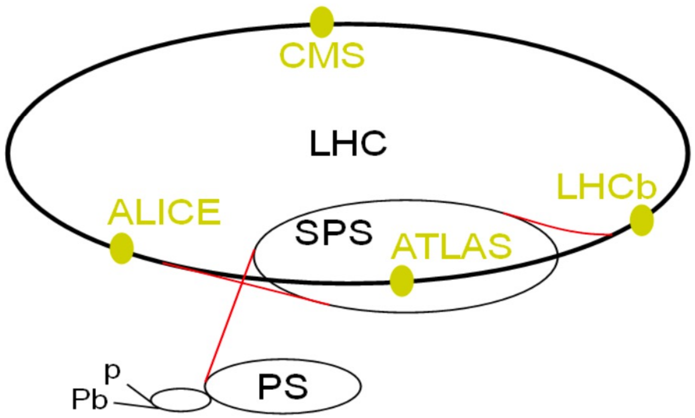
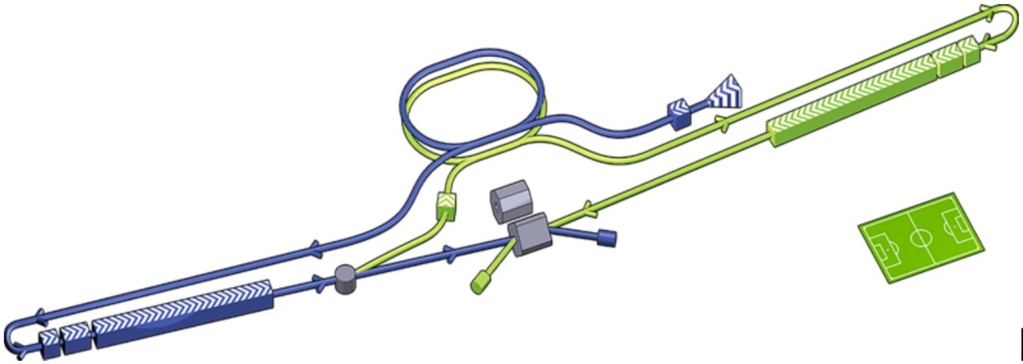
X. Luo, H. B. Fu, and H. J. Tian, Chin. Phys .C 47 (2023) 5, 053102.

Background



CEPC



ILC

- **Relatively clean background**
- **High resolution and detection ability**

CEPC	Super-Z	$L \simeq 10^{34-36}\,cm^{-2}s^{-1}$
ILC	GigaZ	$L \simeq 0.7\times10^{34}cm^{-2}s^{-1}$

Content

Calculation Technology

Within the framework of NRQCD, the typical physical process is:

$$e^+ + e^- \to \gamma^*/Z^* \to \Xi_{QQ'} + \overline{Q'} + \overline{Q}$$

$$\sigma(e^+e^- \to \Xi_{QQ'} + \bar{Q}' + \bar{Q}) = \sum \hat{\sigma}\left(e^+e^- \to \langle QQ'\rangle[n] + \bar{Q}' + \bar{Q}\right)\langle \mathcal{O}^H[n]\rangle$$

perturbative region

nonperturbative region

Nonperturbative region：

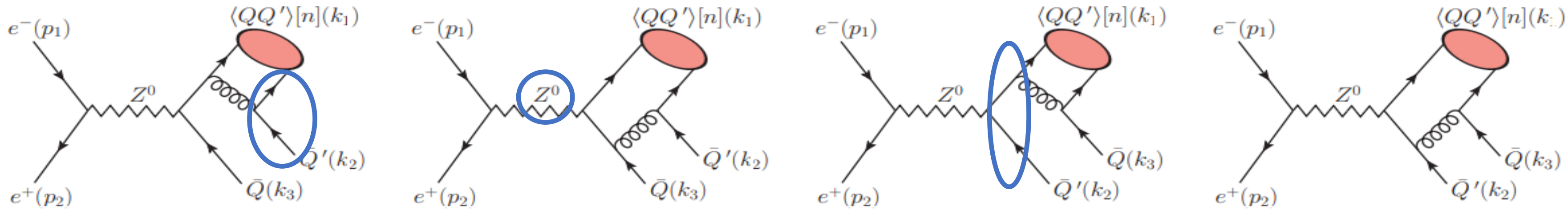
Radial wave function at the origin （S-wave） $\langle \mathcal{O}^H[S]_{\bar{\mathbf{3}}}\rangle = |\Psi(0)|^2 = \frac{1}{4\pi}|R(0)|^2,$

Its first derivative （P-wave） $\langle \mathcal{O}^H[P]_{\bar{\mathbf{3}}}\rangle = |\Psi'(0)|^2 = \frac{3}{4\pi}|R'(0)|^2.$

Perturbative region：

The differential cross section： $d\hat{\sigma}\left(e^+e^- \to \langle QQ'\rangle[n] + \bar{Q}' + \bar{Q}\right) = \frac{\overline{\sum}|\mathcal{M}[n]|^2 d\Phi_3}{4\sqrt{(p_1\cdot p_2)^2 - m_e^4}}$

Calculation Technology



(a) (b) (c) (d)

S-wave amplitude:

X. Luo, H. B. Fu, and H. J. Tian, Chin. Phys .C 47 (2023) 5, 053102.

$$C = -i\gamma^2\gamma^0$$

$$\Gamma^{\mu}_{Zc} = \gamma^{\mu}\left[\alpha\left(\frac{1}{4}-\frac{2}{3}\sin^2\theta_w\right)-\frac{\gamma^5}{4}\right],$$

$$\Gamma^{\mu}_{Zb} = -\gamma^{\mu}\left[\alpha\left(\frac{1}{4}-\frac{1}{3}\sin^2\theta_w\right)-\frac{\gamma^5}{4}\right],$$

α → 1 → $Z_0-Q-\overline{Q}$ 顶点

α → -1 → $Z_0-Q'-\overline{Q'}$ 顶点

The diquark mass: $M_{QQ'} = m_Q + m_{Q'}$

$$k_{11} = \frac{m_Q}{M_{QQ'}}k_1 + k, \qquad k_{12} = \frac{m_{Q'}}{M_{QQ'}}k_1 - k$$

k is the relative momentum between these two constituent quarks of the diquark

Calculation Technology

P-wave amplitude:

$$\mathcal{M}_a[^1P_1] = \kappa\, \varepsilon^l_\alpha(k_1)\frac{d}{dk_\alpha}\left[\mathcal{L}^\nu_{ss'}\mathcal{D}_{\mu\nu}\bar{u}_i(k_2)\gamma_\rho\frac{\Pi_{[^1S_0]}(k_1)}{(q_2+k_{12})^2}\gamma_\rho\frac{\not{k}_1+\not{k}_2+m_Q}{(k_1+k_2)^2-m_Q^2}\Gamma^\mu_{ZQ}v_j(k_3)\right]\Bigg|_{k=0}, \quad (4)$$

$$\mathcal{M}_b[^1P_1] = \kappa\, \varepsilon^l_\alpha(k_1)\frac{d}{dk_\alpha}\left[\mathcal{L}^\nu_{ss'}\mathcal{D}_{\mu\nu}\bar{u}_i(k_2)\gamma_\rho\frac{\Pi_{[^1S_0]}(k_1)}{(k_2+k_{12})^2}\Gamma^\mu_{ZQ}\frac{-\not{k}_{12}-\not{k}_2-\not{k}_3+m_Q}{(k_{12}+k_2+k_3)^2-m_Q^2}\gamma_\rho v_j(k_3)\right]\Bigg|_{k=0} \quad (5)$$

$$\mathcal{M}_c[^1P_1] = \kappa\, \varepsilon^l_\alpha(k_1)\frac{d}{dk_\alpha}\left[\mathcal{L}^\nu_{ss'}\mathcal{D}_{\mu\nu}\bar{u}_i(k_2)\gamma_\rho\frac{\not{k}_{11}+\not{k}_2+\not{k}_3+m_{Q'}}{(k_{11}+k_2+k_3)^2-m_{Q'}^2}\Gamma^\mu_{ZQ'}\frac{\Pi_{[^1S_0]}(k_1)}{(k_3+k_{11})^2}\gamma_\rho v_j(k_3)\right]\Bigg|_{k=0} \quad (6)$$

$$\mathcal{M}_d[^1P_1] = \kappa\, \varepsilon^l_\alpha(k_1)\frac{d}{dk_\alpha}\left[\mathcal{L}^\nu_{ss'}\mathcal{D}_{\mu\nu}\bar{u}_i(k_2)\Gamma^\mu_{ZQ'}\frac{-\not{k}_1-\not{k}_3+m_{Q'}}{(k_1+k_3)^2-m_{Q'}^2}\gamma_\rho\frac{\Pi_{[^1S_0]}(k_1)}{(k_3+k_{11})^2}\gamma_\rho v_j(k_3)\right]\Bigg|_{k=0}, \quad (7)$$

$$\mathcal{M}_a[^3P_J] = \kappa\, \varepsilon^J_{\alpha\beta}(k_1)\frac{d}{dk_\alpha}\left[\mathcal{L}^\nu_{ss'}\mathcal{D}_{\mu\nu}\bar{u}_i(k_2)\gamma_\rho\frac{\Pi^\beta_{[^3S_1]}(k_1)}{(q_2+k_{12})^2}\gamma_\rho\frac{\not{k}_1+\not{k}_2+m_Q}{(k_1+k_2)^2-m_Q^2}\Gamma^\mu_{ZQ}v_j(k_3)\right]\Bigg|_{k=0}, \quad (8)$$

$$\mathcal{M}_b[^3P_J] = \kappa\, \varepsilon^J_{\alpha\beta}(k_1)\frac{d}{dk_\alpha}\left[\mathcal{L}^\nu_{ss'}\mathcal{D}_{\mu\nu}\bar{u}_i(k_2)\gamma_\rho\frac{\Pi^\beta_{[^3S_1]}(k_1)}{(k_2+k_{12})^2}\Gamma^\mu_{ZQ}\frac{-\not{k}_{12}-\not{k}_2-\not{k}_3+m_Q}{(k_{12}+k_2+k_3)^2-m_Q^2}\gamma_\rho v_j(k_3)\right]\Bigg|_{k=0} \quad (9)$$

$$\mathcal{M}_c[^3P_J] = \kappa\, \varepsilon^J_{\alpha\beta}(k_1)\frac{d}{dk_\alpha}\left[\mathcal{L}^\nu_{ss'}\mathcal{D}_{\mu\nu}\bar{u}_i(k_2)\gamma_\rho\frac{\not{k}_{11}+\not{k}_2+\not{k}_3+m_{Q'}}{(k_{11}+k_2+k_3)^2-m_{Q'}^2}\Gamma^\mu_{ZQ'}\frac{\Pi^\beta_{[^3S_1]}(k_1)}{(k_3+k_{11})^2}\gamma_\rho v_j(k_3)\right]\Bigg|_{k=0} \quad (10)$$

$$\mathcal{M}_d[^3P_J] = \kappa\, \varepsilon^J_{\alpha\beta}(k_1)\frac{d}{dk_\alpha}\left[\mathcal{L}^\nu_{ss'}\mathcal{D}_{\mu\nu}\bar{u}_i(k_2)\Gamma^\mu_{ZQ'}\frac{-\not{k}_1-\not{k}_3+m_{Q'}}{(k_1+k_3)^2-m_{Q'}^2}\gamma_\rho\frac{\Pi^\beta_{[^3S_1]}(k_1)}{(k_3+k_{11})^2}\gamma_\rho v_j(k_3)\right]\Bigg|_{k=0}, \quad (11)$$

Calculation Technology

The overall parameter $\kappa = \frac{Cg^2 g_s^2}{\cos^2\theta_W}$, $\Gamma^{\mu}_{ZQ^{(\prime)}}$ means the interaction vertex 。

The leptonic vector：

$$\mathcal{L}^{\nu}_{ss'} = \bar{\nu}_s(p_2)\gamma^{\nu}\left(\sin^2\theta_w + \frac{\gamma^5}{4} - \frac{1}{4}\right)u_{s'}(p_1)$$

Z^0 propagator：

$$\mathcal{D}_{\mu\nu} = \frac{i}{p^2 - m_Z^2 + i m_Z \Gamma_Z}\left(-g_{\mu\nu} + \frac{p_\mu p_\nu}{p^2}\right)$$

The sum formulas of polarization vector and polarization tensor satisfy：

$$\sum_{l_z} \varepsilon^l_\alpha \varepsilon^{l*}_{\alpha'} = \Pi_{\alpha\alpha'},$$

$$\varepsilon^0_{\alpha\beta}\varepsilon^{0*}_{\alpha'\beta'} = \frac{1}{3}\Pi_{\alpha\beta}\Pi_{\alpha'\beta'},$$

$$\sum_{J_z} \varepsilon^1_{\alpha\beta}\varepsilon^{1*}_{\alpha'\beta'} = \frac{1}{2}\left(\Pi_{\alpha\alpha'}\Pi_{\beta\beta'} - \Pi_{\alpha\beta'}\Pi_{\alpha'\beta}\right),$$

$$\sum_{J_z} \varepsilon^2_{\alpha\beta}\varepsilon^{2*}_{\alpha'\beta'} = \frac{1}{2}\left(\Pi_{\alpha\alpha'}\Pi_{\beta\beta'} + \Pi_{\alpha\beta'}\Pi_{\alpha'\beta}\right) - \frac{1}{3}\Pi_{\alpha\beta}\Pi_{\alpha'\beta'}$$

Where $\Pi_{\alpha\beta} = -g_{\alpha\beta} + \frac{p_{1\alpha}p_{1\beta}}{M^2_{QQ'}}$.

The color factor：

$$\mathcal{C}_{ij,l} = \frac{1}{\sqrt{2}} \times \sum_{a=1}^{8}\sum_{m,n=1}^{3}(T^a)_{mi}(T^a)_{nj} \times G_{mnl}$$

$\bar{3}$ → $\varepsilon_{mnl}\varepsilon_{m'n'l} = \delta_{mm'}\delta_{nn'} - \delta_{mn'}\delta_{nm'}$,

6 → $f_{mnl}f_{m'n'l} = \delta_{mm'}\delta_{nn'} + \delta_{mn'}\delta_{nm'}$

For the production of color $\bar{3}$ state or color 6 state, $C_{ij,l}^2$ is 4/3 or 2/3 respectively.

Content

Results : Cross section

Tools：Mathematica，FeynArts、FeynCalc and FormCalc。

Tavble I and II Cross sections (in unit: fb) and events (in unit: 10^2) for doubly heavy baryons produced at the Super-Z factory and GigaZ, respectively.

State	Ξ_{cc}						Ξ_{bb}					
	$[^1S_0]_{\mathbf{6}}$	$[^3S_1]_{\bar{\mathbf{3}}}$	$[^1P_1]_{\bar{\mathbf{3}}}$	$[^3P_0]_{\mathbf{6}}$	$[^3P_1]_{\mathbf{6}}$	$[^3P_2]_{\mathbf{6}}$	$[^1S_0]_{\mathbf{6}}$	$[^3S_1]_{\bar{\mathbf{3}}}$	$[^1P_1]_{\bar{\mathbf{3}}}$	$[^3P_0]_{\mathbf{6}}$	$[^3P_1]_{\mathbf{6}}$	$[^3P_2]_{\mathbf{6}}$
σ	267.02	548.63	11.43	8.23	9.14	3.58	25.94	12.93	0.73	0.61	0.69	0.27
N	267.02	548.63	11.43	8.23	9.14	3.58	25.94	12.93	0.73	0.61	0.69	0.27
$N_{\rm GigaZ}$	186.91	384.04	8.00	5.76	6.40	2.51	18.16	9.05	0.51	0.43	0.48	0.19

State	Ξ_{bc}											
	$[^1S_0]_{\bar{\mathbf{3}}}$	$[^1S_0]_{\mathbf{6}}$	$[^3S_1]_{\bar{\mathbf{3}}}$	$[^3S_1]_{\mathbf{6}}$	$[^1P_1]_{\bar{\mathbf{3}}}$	$[^1P_1]_{\mathbf{6}}$	$[^3P_0]_{\bar{\mathbf{3}}}$	$[^3P_0]_{\mathbf{6}}$	$[^3P_1]_{\bar{\mathbf{3}}}$	$[^3P_1]_{\mathbf{6}}$	$[^3P_2]_{\bar{\mathbf{3}}}$	$[^3P_2]_{\mathbf{6}}$
σ	609.10	304.55	825.00	412.50	17.28	8.64	11.95	5.98	22.24	11.12	21.43	10.72
N	609.10	304.55	825.00	412.50	17.28	8.64	11.95	5.98	22.24	11.12	21.43	10.72
$N_{\rm GigaZ}$	426.37	213.19	577.50	288.75	12.09	6.05	8.37	4.18	15.57	7.79	15.00	7.50

The total cross sections of the excited doubly heavy baryons production are **32.38 fb、109.36 fb and 2.29 fb** respectively。These contributions correspond to **3.97%、5.08% and 5.89%** of the contributions from the total S-wave。

Results : Cross section

One can see that：

- ✓ At the Super-Z factory, the total produced events of the excited Ξ_{cc} , Ξ_{bc} and Ξ_{bb} are :**3.24×10^3, 1.09×10^4, and 2.30×10^2** respectively.

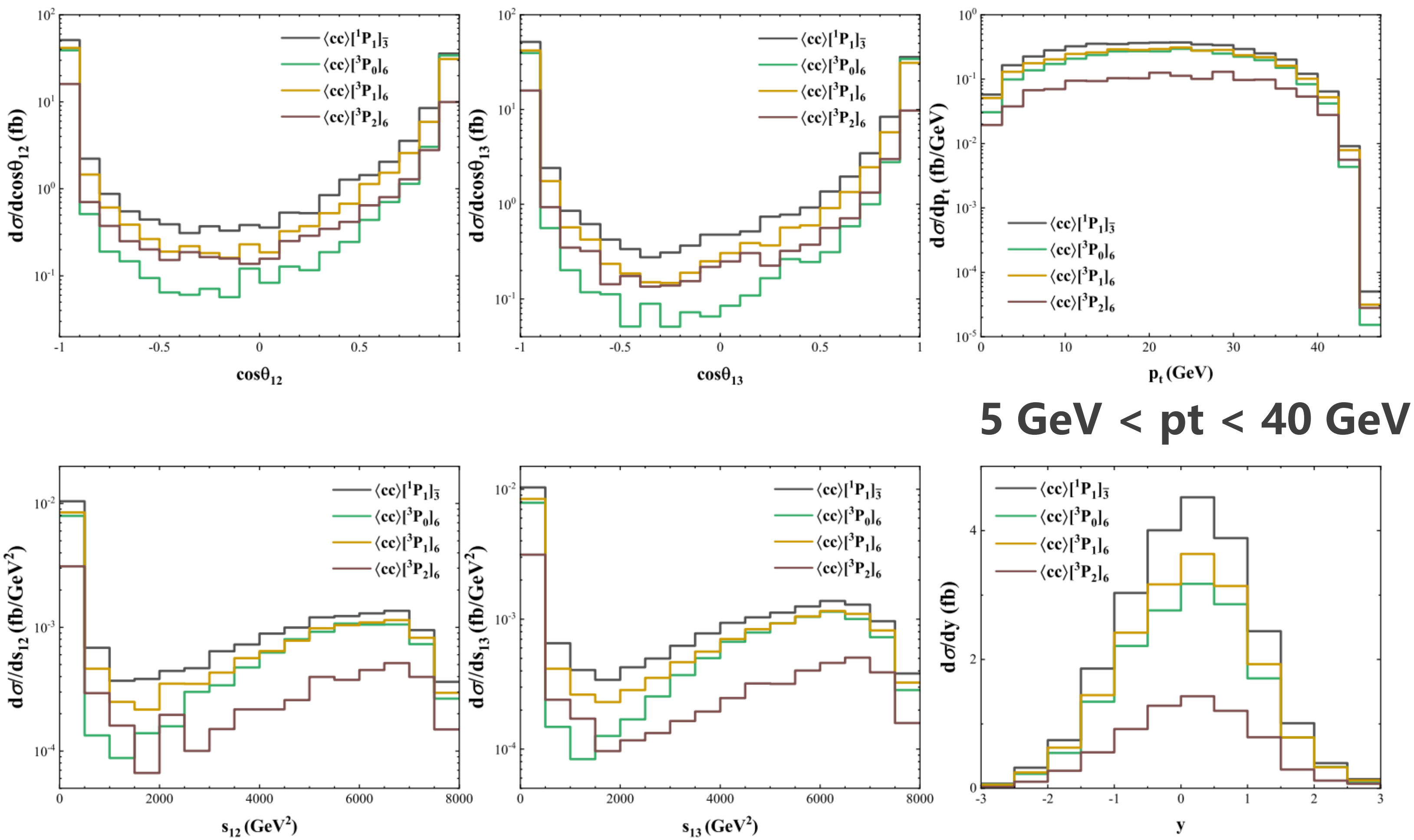
- ✓ At the GigaZ, the total produced events of the excited Ξ_{cc} , Ξ_{bc} and Ξ_{bb} are :**2.27×10^3, 7.66×10^3, and 1.60×10^2** respectively.

- ✓ Assuming that all the considered excited states can decay into the ground state 100 %, the total cross sections for Ξ_{cc} , Ξ_{bc} and Ξ_{bb} production are **848.03 fb, 2260.51 fb, and 41.16 fb**, resulting in a large number of produced events up to **8.48×10^4, 2.26×10^5, and 4.12×10^3**.

- ✓ When the luminosity of the Super-Z factory increases to **10^{36}** $cm^{-2}s^{-1}$, the corresponding produced events of doubly heavy baryons will increase by **100** times.

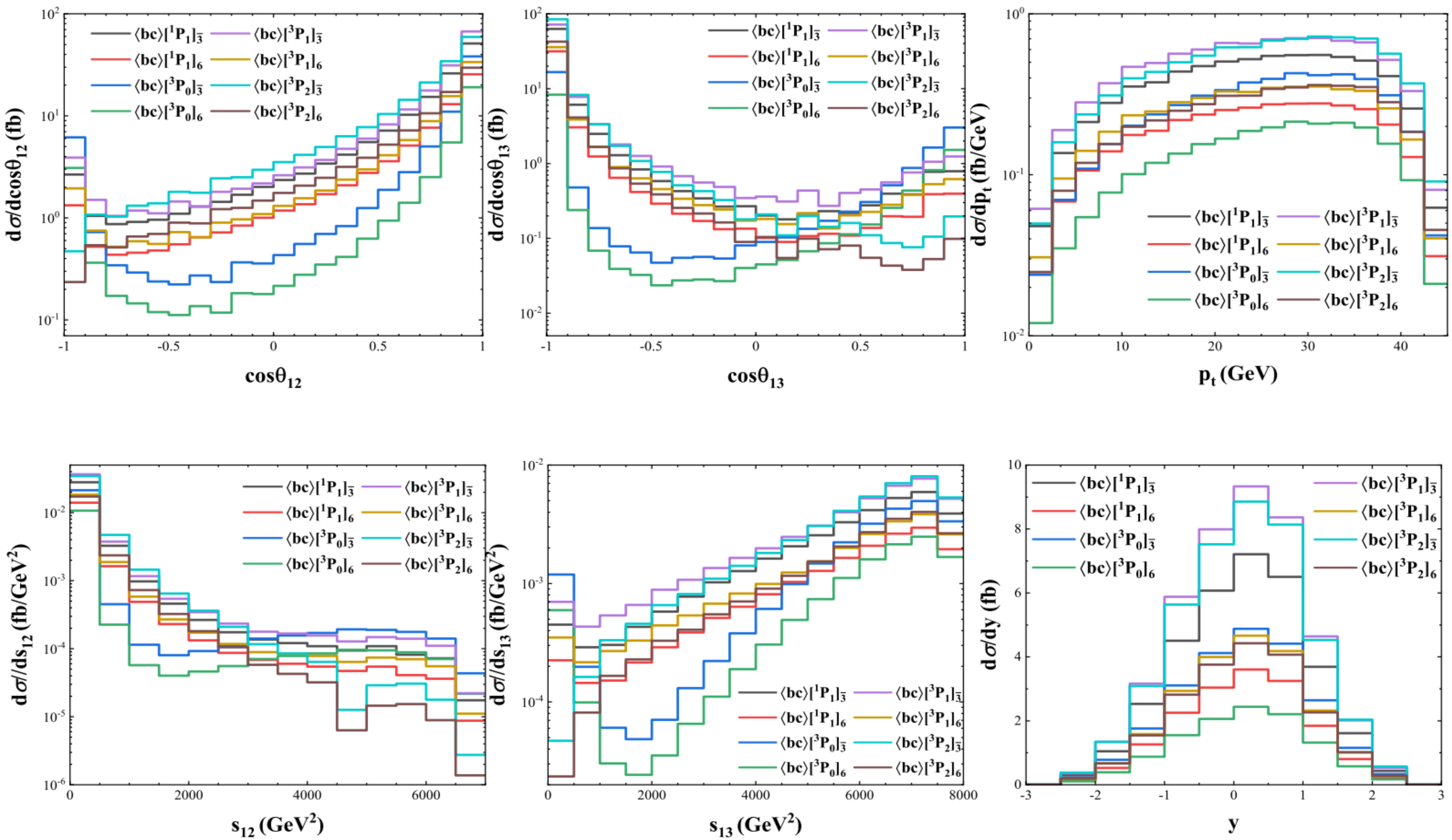
Results : Differential distributions

The differential distributions for the P-wave configurations of $\langle cc\rangle[n]$ diquark at Super-Z factory: $\cos\theta_{12}$, $\cos\theta_{13}$, pt, s_{12}, s_{13} and y。



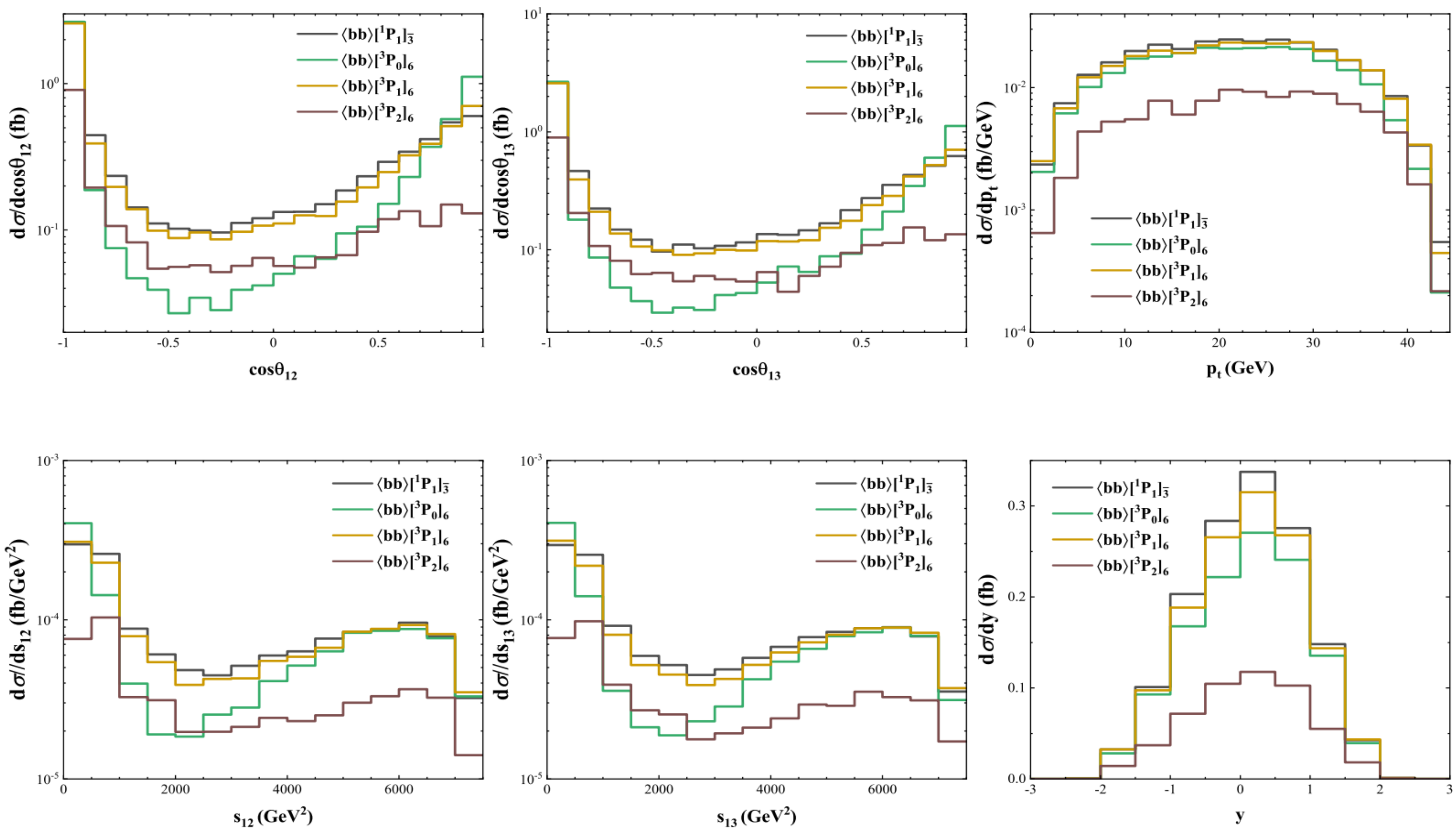
Results : Differential distributions

The differential distributions for the P-wave configurations of ⟨bc⟩[n] diquark at Super-Z factory: $\cos\theta_{12}$, $\cos\theta_{13}$, pt, s_{12}, s_{13} and y。



Results : Differential distributions

The differential distributions for the P-wave configurations of ⟨bb⟩[n] diquark at Super-Z factory: $\cos\theta_{12}$, $\cos\theta_{13}$, pt, s_{12}, s_{13} and y。



Results : uncertainties

Heavy quark mass, mc and mb:

m_c (GeV)	1.5	1.65	1.8	1.95	2.1
$\sigma_{\Xi_{cc}}([{}^1P_1]_{\bar{\mathbf{3}}})$	28.86	17.80	11.43	7.60	5.20
$\sigma_{\Xi_{cc}}([{}^3P_0]_{\mathbf{6}})$	20.57	12.74	8.23	5.50	3.78
$\sigma_{\Xi_{cc}}([{}^3P_1]_{\mathbf{6}})$	23.00	14.20	9.14	6.09	4.18
$\sigma_{\Xi_{cc}}([{}^3P_2]_{\mathbf{6}})$	8.95	5.54	3.58	2.39	1.65
$\sigma_{\Xi_{bc}}([{}^1P_1]_{\bar{\mathbf{3}}})$	42.05	26.37	17.28	11.75	8.25
$\sigma_{\Xi_{bc}}([{}^1P_1]_{\mathbf{6}})$	21.02	13.18	8.64	5.87	4.13
$\sigma_{\Xi_{bc}}([{}^3P_0]_{\bar{\mathbf{3}}})$	24.59	16.82	11.95	8.77	6.60
$\sigma_{\Xi_{bc}}([{}^3P_0]_{\mathbf{6}})$	12.29	8.41	5.98	4.38	3.30
$\sigma_{\Xi_{bc}}([{}^3P_1]_{\bar{\mathbf{3}}})$	51.40	33.11	22.24	15.48	11.11
$\sigma_{\Xi_{bc}}([{}^3P_1]_{\mathbf{6}})$	25.70	16.56	11.12	7.74	5.55
$\sigma_{\Xi_{bc}}([{}^3P_2]_{\bar{\mathbf{3}}})$	57.34	34.30	21.43	13.89	9.29
$\sigma_{\Xi_{bc}}([{}^3P_2]_{\mathbf{6}})$	28.67	17.15	10.72	6.95	4.65

m_b(GeV)	4.7	4.9	5.1	5.3	5.5
$\sigma_{\Xi_{bc}}([{}^1P_1]_{\bar{\mathbf{3}}})$	17.80	17.52	17.28	17.05	16.85
$\sigma_{\Xi_{bc}}([{}^1P_1]_{\mathbf{6}})$	8.90	8.76	8.64	8.53	8.43
$\sigma_{\Xi_{bc}}([{}^3P_0]_{\bar{\mathbf{3}}})$	13.21	12.55	11.95	11.42	10.94
$\sigma_{\Xi_{bc}}([{}^3P_0]_{\mathbf{6}})$	6.60	6.27	5.98	5.71	5.47
$\sigma_{\Xi_{bc}}([{}^3P_1]_{\bar{\mathbf{3}}})$	23.43	22.81	22.24	21.73	21.27
$\sigma_{\Xi_{bc}}([{}^3P_1]_{\mathbf{6}})$	11.71	11.40	11.12	10.87	10.63
$\sigma_{\Xi_{bc}}([{}^3P_2]_{\bar{\mathbf{3}}})$	21.05	21.24	21.43	21.61	21.79
$\sigma_{\Xi_{bc}}([{}^3P_2]_{\mathbf{6}})$	10.52	10.62	10.72	10.81	10.89
$\sigma_{\Xi_{bb}}([{}^1P_1]_{\bar{\mathbf{3}}})$	1.14	0.91	0.73	0.59	0.48
$\sigma_{\Xi_{bb}}([{}^3P_0]_{\mathbf{6}})$	0.94	0.76	0.61	0.50	0.41
$\sigma_{\Xi_{bb}}([{}^3P_1]_{\mathbf{6}})$	1.06	0.85	0.69	0.56	0.46
$\sigma_{\Xi_{bb}}([{}^3P_2]_{\mathbf{6}})$	0.41	0.33	0.27	0.22	0.18

Results : uncertainties

Radial wave functions:

Table III: Radial wave functions at the origin and their first derivatives of the ⟨cc⟩ -, ⟨bc⟩ -, and ⟨bb⟩ -diquark systems.

State	S-wave			P-wave		
	$\langle cc\rangle$	$\langle bc\rangle$	$\langle bb\rangle$	$\langle cc\rangle$	$\langle bc\rangle$	$\langle bb\rangle$
power-low	0.700	0.904	1.382	-	-	-
K^2O	0.523	0.722	1.345	0.102	0.200	0.479
B.T.	0.530	0.726	1.346	0.128	0.202	0.479

S-wave: $0.582^{+0.118}_{-0.059}$, $0.784^{+0.120}_{-0.062}$, and $1.358^{+0.024}_{-0.013}$ $\mathrm{GeV}^{3/2}$

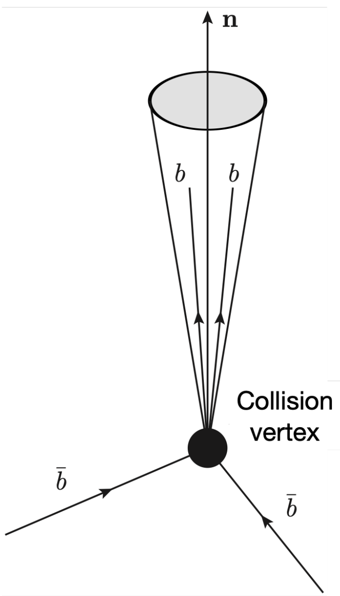
P-wave: 0.115 ± 0.013, 0.201 ± 0.01, and 0.479 ± 0 $\mathrm{GeV}^{5/2}$

Total cross section: $604.93^{+129.97}_{-117.3}$, $1728.90^{+533.81}_{-458.14}$ and $39.81^{+1.36}_{-1.33}$ fb

Discussion: doubly heavy tetraquarks

*[A.Ali, Parkhomenko, **QQ**, W. Wang,1805.02535]*
*[A.Ali, **QQ**, W. Wang,1806.09288]*
*[**QQ**, F.S.Yu, arXiv:2008.08026]*

Production Mechanism



- It was propose for double-bottom hadron production

[Ali,Parkhomenko,**QQ**,Wang,1805.02535;Ali,**QQ**,Wang,1806.09288]

1. Two produced heavy quarks stay close enough to form a heavy diquark
2. The heavy diquark further fragments into doubly heavy hadrons

- Assuming T_{cc} a real tetraquark, the same mechanism applies
- Stay close enough? One parameter ——

$$\Delta M \equiv M_{cc} - 2m_c \leq (2.0^{+0.5}_{-0.4})\ \text{GeV}$$

Cut-off value

Determined by matching the B_c production rate to $\bar{b}b\bar{c}c$

x

The invariant mass of the two heavy quarks $m_{QQ'}$ is used to parameterize their collinear level

Discussion: doubly heavy tetraquarks

Production of double-charm hadrons

With partonic simulation by MadGraph & Pythia, we obtain

- The cross section for all double-charm hadrons

  $\sigma(pp \to H_{cc} + X) = (310^{+170}_{-70})$ nb;

- For double-charm baryons, e.g.

  $\sigma(\Xi_{cc}^{++}) = (103^{+56}_{-22})$ nb

- For double-charm tetraquarks, e.g.

  $\sigma(T_{cc}^{+}) = (24^{+14}_{-7})$ nb

The cuts are $4 < p_T < 15$ GeV, $2 < \eta < 4.5$ @ 13 TeV LHCb

Comparison with theory

vs 62 nb (NRQCD)

[Chang,Qiao,Wang,Wu,0601032]

Comparison with experiment

vs [30, 130] nb
(LHCb with theory inputs)

$$\frac{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$$

[LHCb,1910.11316]

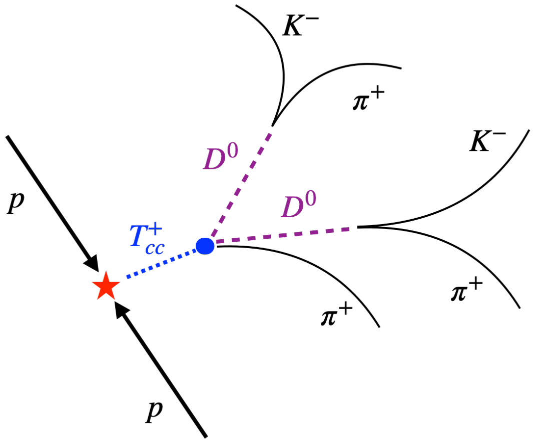
x

Discussion: doubly heavy tetraquarks

Detection of T_{cc}

Propose the golden channel $T_{cc}^{+} \to D^0 D^{*+} \to D^0 D^0 \pi^+$

- Big branching ratio
- Big detection efficiency (all charged particles)



Compared with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

Production $\sigma(\Xi_{cc}^{++}) = (103^{+56}_{-22})$ nb, $\sigma(T_{cc}^{+}) = (24^{+14}_{-7})$ nb $\Rightarrow$ $\frac{f_{T_{cc}}}{f_{\Xi_{cc}}} \sim \frac{1}{4}$

Decay $Br(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)\ Br(\Lambda_c^+ \to p K^- \pi^+)$ one more track

10% 6% 1/3

$Br(T_{cc} \to D^0 D^{*+})\ Br(D^{*+} \to D^0 \pi^+)\ Br(D^0 \to K^- \pi^+)^2$

1/2 2/3 x (4%)^2

$\Rightarrow$ $Br(T_{cc})/Br(\Xi_{cc}^{++}) \sim 1/4$

Discussion: doubly heavy tetraquarks

Detection of T_{cc}

$f_{T_{cc}}/f_{\Xi_{cc}} \sim 1/4$

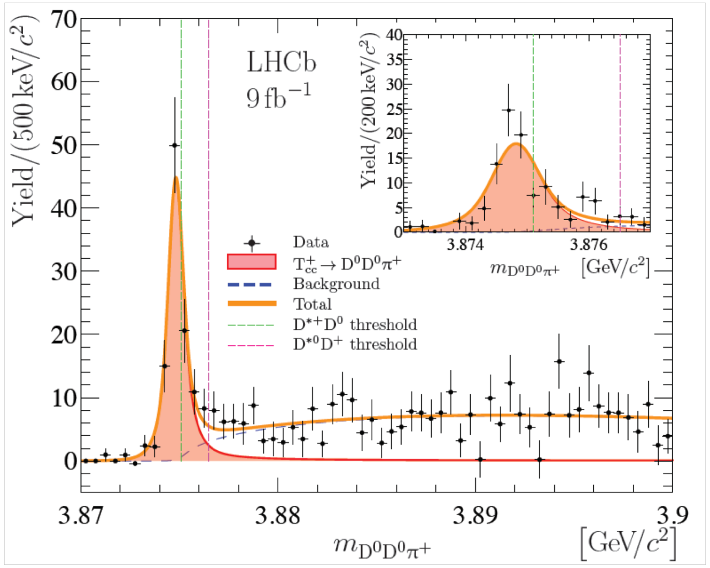
$Br(T_{cc})/Br(\Xi_{cc}^{++}) \sim 1/4$

1500 events of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

T_{cc}^+: $N_s \sim 100$

[**QQ**,Shen,Yu, 2008.08026]

x



Parameter	Value
N	117 ± 16
δm_{BW}	-273 ± 61 keV/c^2
Γ_{BW}	410 ± 165 keV

[LHCb,2109.01038;2109.01056]

Discussion: doubly heavy tetraquarks

Production: results

- Crosscheck with LHCb and NRQCD (Ξ_{cc}^{++} production at LHC)

$\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \approx 103$ nb ⟷ 30 ~ 130 nb (LHCb) [LHCb, 1902.06794]
62 nb (NRQCD) [Chang, Qiao, Wang, Wu, '06]

- A brief summary

No. of events	$T^{\{cc\}}_{[\bar{u}\bar{d}]}$	$T^{\{bc\}}_{[\bar{u}\bar{d}]}$	$T^{\{bb\}}_{[\bar{u}\bar{d}]}$	Ξ_{bc}^{+}	Ξ_{bb}^{0}	Ξ_{cc}
LHCb (10 fb^{-1})	2.4×10^{8}	8.8×10^{8}	2.4×10^{7}	1.4×10^{9}	3.8×10^{7}	-
CEPC (Tera-Z)	4.1×10^{6}	-	10^{6}	-	1.6×10^{6}	-
CEPC (NRQCD)	-	-	-	$4.12\times10^{3-5}$	$2.26\times10^{5-7}$	$8.48\times10^{4-6}$

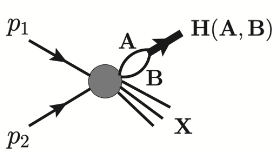
[A.Ali, Parkhomenko, **QQ**, W. Wang,1805.02535]
[A.Ali, **QQ**, W. Wang,1806.09288]
[**QQ**, F.S.Yu, arXiv:2008.08026]
[J.-J. Niu, J.-B. Li, H.-Y. Bi and **H.-H. Ma**, arXiv:2305.15362]

Discussion: doubly heavy tetraquarks

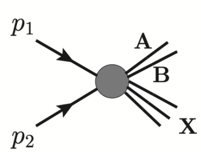
Cross section

- As a tetraquark → $\sigma(T_{cc}^{+}) = (24^{+14}_{-7})$ nb
- As a molecule state → $\sigma(T_{DD^*}) \approx 0.3$ nb

$pp \to D + D^* + X \to T(DD^*) + X$



$$= \int \frac{d^3k}{(2\pi)^3} \Phi(\vec{k}) \times$$



$$\sim \Psi(0) \times A(pp \to D + D^* + X)$$

(Input $\Psi(0) = 0.14$ GeV$^{3/2}$)

[Li,Sun,Liu,Zhu,1211.5007]

2 orders of magnitude lower!

Prefer a tetraquark…

Further cross section measurements at CEPC and LHCb will determine its nature more clearly!

Content

Summary

The event for production of doubly heavy baryons at CEPC

Events	Ξ_{cc}	Ξ_{bc}	Ξ_{bb}
Direct production	$4.12\times10^{3-5}$	$2.26\times10^{5-7}$	$8.48\times10^{4-6}$
Indirect production (Top decay)	$-$	$2.36\times10^{4-6}$	$9.73\times10^{2-4}$
Indirect production (Higgs decay)	0.41×10^{4}	6.35×10^{4}	0.28×10^{4}
Indirect production (Z decay)	8.1×10^{6}	2.48×10^{7}	1.19×10^{6}

$e^+ + e^- \to Z^0 \to \Xi_{QQ'} + \overline{Q}' + \overline{Q}$ *J.-J. Niu, J.-B. Li, H.-Y. Bi and* ***H.-H. Ma****, arXiv:2305.15362.*

$t \to \Xi_{bQ} + \overline{Q} + W^+$ *J. J. Niu, L. Guo,* ***H. H. Ma*** *and X. G. Wu, Eur. Phys. J. C 79, no.4, 339 (2019).*
H. H. Ma *and J. J. Niu, Eur. Phys. J. C 83, no.1, 5 (2023).*

$H \to Q\overline{Q}/Q'\overline{Q}' \to \Xi_{QQ'} + \overline{Q} + \overline{Q}'$ *J. J. Niu, L. Guo,* ***H. H. Ma****, X. G. Wu and X. C. Zheng, Phys. Rev. D 98, no.9, 094021 (2018).*
H. H. Ma*, J. J. Niu and X. C. Zheng, Phys. Rev. D 107, no.1, 014006 (2023).*

$Z \to \Xi_{QQ'} + \overline{Q} + \overline{Q}'$ *X. Luo, H. B. Fu, and H. J. Tian, Chin. Phys .C 47 (2023) 5, 053102.*
H. J. Tian , X. Luo, and, H. B. Fu, arXiv: 2306.03388 .

Summary

- The **total cross sections and relevant events** for the production of excited Ξ_{cc} , Ξ_{bc} and Ξ_{bb} baryons from the P-wave diquark state at the Super-Z factory with $\mathscr{L} \simeq 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in one operational year are：

$$\sigma_{\Xi_{cc}} = 32.38\ \mathrm{fb}, \qquad \mathrm{N}_{\Xi_{cc}} = 3.24 \times 10^3;$$
$$\sigma_{\Xi_{bc}} = 109.36\ \mathrm{fb}, \qquad \mathrm{N}_{\Xi_{bc}} = 1.09 \times 10^4;$$
$$\sigma_{\Xi_{bb}} = 2.30\ \mathrm{fb}, \qquad \mathrm{N}_{\Xi_{bb}} = 2.30 \times 10^2;$$

- To provide some guidance for experimental measurements, the relevant transverse momentum, rapidity, angular, and invariant mass **distributions** are presented

- The largest contributions can be achieved when the excited $\Xi_{QQ'}$ baryons and $\overline{Q}'$ (Q') are moving **side by side or back to back**.

- There are obvious **backward-forward asymmetry** in the rapidity distributions

$$e^+ + e^- \to Z^0 \to \Xi_{QQ'} + \overline{Q'} + \overline{Q}$$

Thanks for your attention！